Diffractive-optical processing of temporal signals, part II: optical tapped-delay line

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The topic of this presentation is the utilization of time for optical information processing. As clock rates in computing and communication systems increase and reach the THz border, optical techniques for signal filtering, shaping and clock distribution become attractive. We discuss the use of optics in temporal processing and consider in particular diffractive solutions. In this paper, we describe the use of double diffraction for implementing an ultrafast tapped-delay line.
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Two developments of recent years have made it possible to generate and process wavefronts in a very flexible way: first, computer algorithms (and speed of the computation) and second, micro/nano-technology for generating computer-generated elements. This combination of computer-based design and lithographic fabrication was, in principle, already used in the 1960s to make the first computer-generated holograms[1−3]. Since then new tools have been developed such as the iterative Fourier-transform algorithms due to, for example, Gerchberg and Saxton[4].

The fabrication of diffractive elements by means of microlithography was demonstrated already in the late 1960s[5,6]. Since then a large number of implementations and improvements have been demonstrated and applied to different areas of optical information technology like beam splitting, shaping, storage, imaging, interconnection, systems integration, etc.. Overviews of different techniques and applications are given in Ref. [7—9]. An example of an optical light distribution generated by a lithographically fabricated diffractive optical element is shown in Fig. 1[10].

The basic principle of combining computer simulation and design on the one hand with lithographic structuring on the other has continued since the 1960s all the way down to the nanoscale. Photonic crystals are an important class of nanoscopic devices which hold promise for realizing compact opical and optoelectronic devices[11]. Here, the need for "smart" modeling approaches is important in order to minimize computing time. A specific approach is based, for example, on the concept of Floquet modes and described in Ref. [12].

Fig. 1. Output of a computer-generated diffractive optical element calculated by an interative design algorithm.

Communications systems comprise optics for transmission and electronics for switching purposes. Current communication systems operate at 40 Gb/s. However, this is well below the bandwidth of optical fibers. Just considering the bandwidth of an optical fiber, individual time division multiplexed (TDM) communication channels with data rates > 1 Tb/s would be possible. While this is hard to achieve for the optics, it may be even harder for electronics. The fastest electronic devices run at approximately 600 GHz. Hence, in order to break the 1 THz boundary, more tasks in the system have to be accomplished by optical means. One of them is linear processing, as used, for example, in filtering systems. Recently, several approaches have been studied to implement filters for all-optical networks[13]. A specific approach is the use of integrated optical ring resonators, which allows one to realize infinite impulse response (IIR) filter structures[14]. Here, we want to discuss an approach to implement a finite impulse response (FIR) filter based on the self-imaging phenomenon. Our goal is to build a filter for the 1—10 THz regime.

Viénot and Froehly were probably the first to discuss the temporal processing of optical signals in detail[15]. In their work they make use of the principle of detour phase illustrated here in Fig. 2. A grating of period p introduces time delays $\tau = p\sin\alpha/c = \lambda/c$ between the beamlets traveling in the direction α of the first diffraction order. The impulse response of a diffraction grating is given as a sequence of delta peaks as shown in Fig. 3. Its Fourier transform is the transfer function. The free spectral range (FSR) $\Delta\nu_t$ is given by the inverse of the time delay τ.

Due to the short temporal delay $\tau = \lambda/c$, grating spectrometers operate at a free spectral range in the optical

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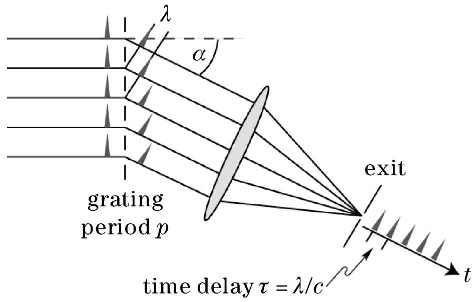

Fig. 2. Optical grating diffraction as tapped-delay line: in direction α, the grating generates time delays $\tau = p \sin \alpha / c$ where p is the grating period.

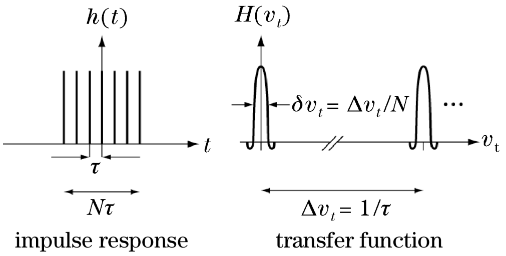

Fig. 3. A linear filter can be described by its impulse response $h(t)$ in the temporal domain or equivalently, by its transfer function $\tilde{H}(\nu_t)$ in the frequency domain.

frequency domain, i.e., at $\nu_t \geq 100$ THz. For the purpose we discussed above, namely optical communication systems, this value is too large by one to two orders of magnitude. In order to shift the FSR to a smaller frequency and still use a grating-based FIR, we would have to implement larger time delays by one to two orders of magnitude. One possibility to achieve that is to operate the device in a higher diffraction order, say the Mth order. In that case, the delays are increased by the factor M and the value of the FSR is reduced correspondingly. An arrayed-waveguide grating (AWG)[16,17] would be a possible implementation for this approach. AWGs are usually operated at very high orders, typically $M = 50, \cdots, 100$. However, AWGs are expensive devices on the one hand and they are difficult to handle thermally. Here, we suggest to use another approach based on self-imaging and double-diffraction.

Self-imaging is usually known from the Talbot effect[18] which occurs for laterally periodic wavefields (period p). Self-imaging means that the wavefield (which is assumed to be monochromatic) replicates itself along the z-direction with period $z_{\mathrm{T}} = 2p^2/\lambda$, called the "Talbot distance". By using two gratings, as shown in Fig. 4, one can build a Talbot interferometer[19]. Talbot interferometers have been used for applications in wavefront testing[19] and resonator coupling[20,21], for example. Recently, the use of a Talbot interferometer as a temporal filter was demonstrated[22,23] using the setup shown in Fig. 4. It uses a first beam splitter grating, to split an incoming signal into different diffraction orders. After propagation over a multiple of the Talbot distance a second grating is used to combine the different diffraction orders into a single output beam. This works efficiently if both gratings are phase gratings and if G_2 is phase-complementary to G_1. The temporal behaviour of a

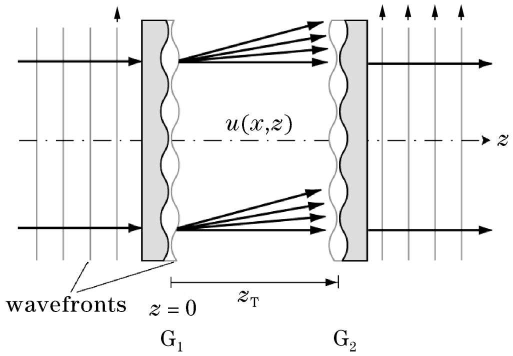

Fig. 4. Talbot interferometer as an optical tapped-delay line filter. Grating G_1 is used to split up the incoming beam into N orders. By placing a phase-complementary grating G_2 in one of the Talbot planes (here: the first Talbot plane), it combines the different diffraction orders into a single output beam. In the temporal domain, a delay occurs between the different diffraction orders.

Talbot interferometer was measured recently[24].

A generalization, more suitable for implementing a FIR filter, is based on Montgomery self-imaging[25]. Whereas in the Talbot case, the spatial frequencies of the wavefield are given as $\nu_{x,n}^{\mathrm{T}} = n\nu_1 = n/p$, in the case of Montgomery self-imaging one has $\nu_{x,n}^{\mathrm{M}} \approx \sqrt{n}\nu_1$. The latter expression holds in the case of the paraxial approximation. Unlike the Talbot-effect, however, the Montgomery-case of self-imaging is not limited to paraxial propagation. A Montgomery wavefield can be implemented by using a Fabry-Perot filter[26] or by using diffractive optics[27]. Going beyond the paraxial case does not represent any problem in theory, but possibly for the implementation of the diffractive optics.

The temporal aspects of Fresnel propagation have been analyzed recently for simple gratings[28] and double grating setups[29,30]. In particular, it was shown that a Montgomery interferometer acts as an FIR filter where the dispersive behaviour and the response function can be adjusted. Various experimental steps will be necessary to demonstrate its use as a filter for the Tb/s-domain. One is to "slow down" its operation to the $1, \cdots, 10$ THz regime. In our experiments so far, the FSR was λ/c. In order to increase this value and operate the filter in the THz band, the use of multimode waveguides might be suitable[31−33]. The propagation of a multimode Montgomery wavefield inside such a waveguide is visualized by simulation shown in Fig. 5[34]. Here, the length of

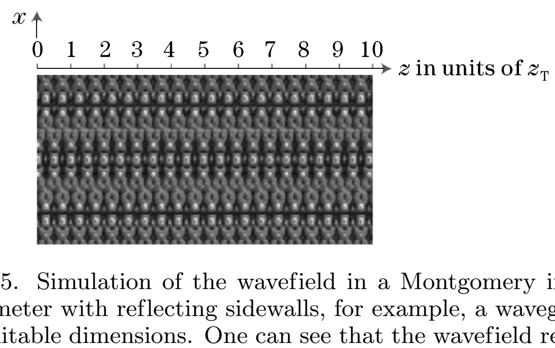

Fig. 5. Simulation of the wavefield in a Montgomery interferometer with reflecting sidewalls, for example, a waveguide of suitable dimensions. One can see that the wavefield reproduces itself along the direction of propagation, although it is not laterally periodic.

the waveguide is assumed to be $L = 10z_{\mathrm{T}}$. The physical length of such a device would be on the order of 10 mm.

Optics or photonics has a powerful competitor: electronics. For several decades, electronics has continued to increase its bandwidth. However, a physical limit exists at around 1 THz. Optical devices, in particular, those suitable for integration typically operate at frequencies of 100 THz and more. Electronics can do almost everything, optics often needs the help of electronics. An optimal technology might comprise both, electronics and optics. For future optoelectronic information processing systems, it is necessary that both meet in the temporal frequency domain. "Diffractive optics" — the art of controlling the propagation of light signals by suitable technological means — can play an important role for realizing suitable optical devices for the THz domain.

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